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Pulp Pumping and Hydraulics

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Pulp Pumping and Hydraulics

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1. Overview of Pumping Needs and Trends

No other non-Newtonian fluid is pumped in larger volumes than wood fiber suspensions, and yet these suspensions remain one of the least understood industrial flows. In the past, pulp operations at low consistency (less than 6%) were commonplace. In the bleach plant, chemical addition and mixing, pulp discharge from storage towers, and dilution and washing historically were done at low consistency. Conventional centrifugal pumping strategies were usually adequate. Where higher consistencies had to be pumped, positive displacement pumps were the standard, but significant pumping at elevated consistencies was generally avoided.

Now, however, there are strong incentives to operate at higher consistency wherever possible. The advantages of higher consistency include lower energy

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costs to pump and heat water, less capital equipment when diluting and thickening operations are eliminated, more compact equipment and facilities, chemical savings when less diluting water is present during bleach addition, and decreased effluent volume (a major environmental and economic consideration).

Since the late 1950s, many bleaching and transfer systems have employed medium to high consistency (10-18%) pumping to decrease water use, energy use, and pulp storage space. These "thick stock" systems accept the various sized lumps of wet stock and air, and displace it into a pipe for mixing, heating, bleaching, refining, or transport to storage. In the past decade, a need has developed to process the higher consistency pulps at pressures up to 1.4 MPa (200 psi) and with significantly less air content as newer bleaching processes replace chlorine bleaching.

Recently, significant gains have been made in pumps for medium-consistency pulp slurries, but feedback from the industry suggests that even greater gains are needed. It also appears that a fundamental understanding of medium and high-consistency flows does not yet exist to adequately guide equipment development.

While medium consistency technology will grow in importance, low consistency pumping operations will continue to be significant. Both processes will be discussed below. We will first review the behavior of pulp suspensions relevant to pumping and pipelines, and will then discuss pumping strategies.

2. Pulp suspension behavior

2.1. Low consistency flows

The unique characteristics of pulp suspensions in pipe flow have been reported by many authors (1-9), and will only be touched upon here. The ability of fibers to entangle and form a network dominates the physics of pulp suspension flow. The fibrous network causes high head losses at low velocities; sometimes leads to plugging, especially in contracting channels or small passages; and entrains air bubbles. The behavior of the pulp suspension depends strongly on consistency and flow rate within a given pipe. Loosely following Duffy et al. (2), we will mention several common effects in terms of Figure 1, which is a typical logarithmic head loss-velocity curve for a low consistency pulp suspension. In the region from A to B, plug flow of the fibrous network occurs. Near or slightly beyond B, at a higher velocity, a clear annulus of water with laminar flow may form around the plug; the annulus tends to be thin, typically less than a fiber length. (In some short-fibered or mechanical pulps, the maximum at point B may be suppressed.) Near C, turbulence in the annulus is apparent, with the fibers still forming a plug in the center. The plug will be increasingly disrupted and begin to shrink at some point between C and E.

At point D, the pressure drop in the suspension is the same as in pure water at the same liquid velocity. This marks the onset of drag reduction, for at higher velocities the friction losses are less than for pure water, in spite of the higher apparent viscosity of the suspension. The point of maximum drag reduction occurs at point E. Increases in velocity continue to disrupt the plug until the flow is fully turbulent, perhaps at point F. Drag reduction still occurs, although the degree of drag reduction tends to decrease as velocity increases further. Details of the head loss curve for pulp suspensions can vary widely depending on fiber properties, slurry concentration, and even configuration of the flow loop used in the measurements.

The behavior of a pulp suspension is closely related to the network strength of the flocs. A useful parameter is τ_d, the wall shear stress at the point where the pulp frictional losses and the water frictional losses are equal (point D in Figure 1). This factor is a measure of the stress required to disrupt the network. Moller (10) found that different sets of data for a given pulp type could be collapsed onto a single curve if the data were plotted in terms of a dimensionless pressure loss term,

$$\frac{\left(\frac{\Delta P}{L}\right)D}{4\tau_d},$$

versus a dimensionless velocity term,

$$\left(\frac{V^5\rho^2\mu}{\tau_d^3 D}\right)^{1/6},$$

where $\Delta P/L$ is the pressure drop per unit distance, D is the pipe diameter, V is the average velocity, ρ is the liquid density, and μ is the viscosity.

Methods for estimating friction losses and for optimizing pipeline design are well described in several recent references (11-16). Pumping operations in the bleach plant tend to fall in the range of regimes A to B, though flows in static mixers or in centrifugal pump impeller zones may be in the C to E regime.

Details of flow behavior are related to characteristics of the pulp fibers themselves, meaning that flow properties will vary with species (especially between hardwoods and softwoods), with pulping method (e.g., kraft versus mechanical pulping), with the degree of refining, with the bleaching process (if any), and so forth.

In designing a hydraulic system using a centrifugal pump, data are rarely available for the exact pulp type and flow conditions to be used. Typically, friction data for a similar pulp type are used (similar forest of origin, similar pulp processing and treatment), with correction terms to account for differences in temperature, refining, consistency, filler, and other factors. Published data are usually obtained for flow in long, straight runs of pipe, whereas the actual application will include elbows, valves, and other departures from fully developed flow conditions. There is a lack of basic data about the effects of these perturbations, and general rules used to estimate their effect on pressure loss may be significantly in error. For example, elbows increase the pressure drop in Newtonian fluids, but in some cases of pulp flow, elbows may decrease the pressure drop by disrupting part of the plug when plug flow is occurring. In general, predictions of pressure losses and power requirements in the pulp flow systems in a bleach plant may be in error by 25% or more. The calculations made by various vendors may offer widely different predictions about the power and even pump size required for a system.

2.2. Medium consistency flows

The frictional resistance of pulp flowing at a given velocity increases strongly with consistency. In the medium consistency range (8-18%), the strength of the fibrous network imparts a high yield stress to the pulp and allows large volumes of air to be entrained (17). The high flow resistance and the increased air content prohibit the use of conventional centrifugal pumps for medium consistency flow. Figure 2 shows typical results for volumetric air content as a function of consistency. Not only does air fill the eye of the impeller and cause loss of pumping action with a conventional centrifugal design, but the air lowers the density of the stock so much that feeding the stock into the pump becomes a severe problem. A feed chute with medium consistency stock can bridge or jam under the simultaneous conditions of high network strength and low density, especially above 14% consistency.

A major breakthrough in handling medium consistency suspensions was achieved when Gullichsen and Härkönen (18) discovered that these suspensions can "fluidize" at high shear rates, behaving almost like water. This is demonstrated in Figure 3, showing data from a rotational shear tester. It was found that the disruptive shear stress at which fluidization occurs was a simple function of consistency, with no obvious change in mechanisms as consistency increased. This work laid the foundation for centrifugal pumping of medium consistency suspensions (19,20), which will be described below.

Friction calculations in general are done in the same way as for low consistency. For example, some pump manufacturers rely on a modified form of the Bodenheimer equation (21), which can also be used for low-consistency flow:

$$H = 482\, F_1\, F_2\, F_3\, C^{2.35}\, P^{0.15}\, D^{-1.3}$$

where H = friction loss (m water/100 m pipe), C is consistency (% BD), P is the production rate (admt/d), and D is pipe diameter (mm), and F_1, F_2, and F_3 are correction factors for pulp type, pH, and temperature, respectively. This equation applies to pulp which has been deaerated by vacuum. Aerated low consistency pulp may have higher friction losses, while medium consistency pulp that contains air may have substantially lower friction losses.

3. Basic pumping concepts

A wide variety of pump types can be found in bleach plants. We will concern ourselves primarily with centrifugal and positive displacement pumps, which are the typical pump types used for pulp. Detailed descriptions of pump components, hydraulic system design, and pump standards are given in several excellent sources, including publications of the Hydraulic Institute (24-26), *Slurry Transport Using Centrifugal Pumps* by Wilson et al. (34), and Garay's *Pump Application Desk Book* (22).

3.1. Centrifugal pumps

Centrifugal pumps are the most common example of kinetic pumps, in which kinetic energy imparted to the fluid in the pump is partially converted to pressure. In typical centrifugal pumps, a rotating impeller brings fluid to high velocity. The fluid is directed into a spiral volute with a constantly increasing cross-sectional area (see Figure 4). The volute is shaped to produce a uniform velocity of fluid as it moves around the casing and to gradually decelerate the fluid as it leaves the pump. The decrease in velocity as the fluid enters the discharge line converts kinetic energy into pressure. Diffuser vanes may be added between the impeller and the outer casing to help decelerate the fluid and increase the efficiency of converting velocity to pressure.

Impeller design is critical for pump performance. The major categories include open and closed (or shrouded) impellers. The open impeller consists of raised vanes on a plate. The closed impeller has vanes between two plates; the fluid must enter the closed impeller via an open eye on the suction side and pass through the rotating assembly. Closed impellers are most common, for they generally have higher efficiency and less trouble with cavitation. However, closed impellers are more subject to plugging problems and may not be reliable for pulp suspensions. Open impellers can be made with small clearances between the casing and the impeller, an essential feature for good efficiency, but lose efficiency rapidly as the clearances increase from wear. Clearances in closed impellers also increase due to wear, but efficiency decreases only weakly. For high head, large impellers are desired. To operate efficiently at the specified head, a smaller sized or cut impeller is needed. A variety of impellers may be available for a single pump casing to allow the user to operate efficiently under a variety of conditions.

Net Positive Suction Head

The radial acceleration of the flow in an impeller leads to low pressure at the impeller eye and high pressure at the outer casing of the pump. The low pressure region can fall below the vapor pressure of the fluid, leading to the formation of vapor bubbles, or cavitation. These bubbles can suddenly collapse as they pass to higher pressure regions and the sudden collapse can induce intense localized shock waves that may erode and pit a metal surface. Cavitation in pumps is a common cause of pump failure, and is a complex problem with a variety of causes.

Many cavitation problems can be avoided if the fluid head in the suction line is high enough that the low pressure zone near the eye of impeller never drops below the vapor pressure of the fluid. Net positive suction head (NPSH) (or, for positive displacement pumps, net positive inlet pressure, NPIP, following the usage of the Hydraulic Institute) is the difference between the absolute fluid head at the inlet of the pump and the vapor pressure of the fluid (expressed in terms of head of liquid):

$$NPSH = Z + (h_s - h_{vp}) - (h_{fs} + h_i) ,$$

where Z is static head in the suction line, h_s is the pressure above the liquid level, h_{vp} is the vapor pressure of the liquid, h_{fs} is the friction loss in the suction line, and h_i is the head loss at the pump inlet, all expressed in equivalent height of fluid. This value must be greater than the pump manufacturer's specified net positive suction head required (NPSHR) or for positive displacement pumps, the net positive inlet pressure required (NPIPR). NPSHR will be a function of the pump type, the pump speed and the fluid properties. If the NPSH is less than the NPSHR when a pure fluid is pumped, cavitation will occur in the pump, lowering the pump capacity, possibly damaging the pump, and causing excessive vibration in the pipeline. In the case of air-containing stock (dissolved air as well as air bubbles), cavitation in the classic sense (sudden vapor collapse creating shock waves) will be reduced or may not occur (23). Rather, large air and vapor bubbles fill the impeller and cause flow reduction or air binding. The presence of air greatly affects the NPSHR. Manufacturer recommendations are typically based on trials with pure water, and may not apply well to pulp suspensions.

NPSHR is determined empirically by the manufacturer. The Hydraulic Institute has established useful standards for the determination of NPSHR (24). Operating above the NPSHR typically does not mean that cavitation is completely absent: it may take 2 to 20 times the head given by the NPSHR to completely suppress cavitation bubbles, but the degree of cavitation occurring for heads above the NPSHR is usually harmless and does not reduce the available pump head by more than 5% (25). However, for some high energy pumps, maximum cavitation damage may occur at suction heads of two to three times the NPSHR.

Performance curves

Performance curves for centrifugal pumps can show the relationships between pump capacity and efficiency, horsepower, NPSHR, and other factors. Performance curves are typically determined for a specific pump speed, impeller diameter and width, and fluid viscosity. Typical performance curves for one pump speed are shown in Figure 5. A given piping system will also have a characteristic curve of head loss versus flow rate. This system curve can only be modified by changing system head loss (adjusting valves) or by changing the consistency within the system (e.g., by dilution). The intersection of the system head loss curve with the pump head curve gives the flow rate and head loss through the system. Pump suppliers may provide performance curves that show the effect of impeller size and pump speed to assist in the choice of pump operating conditions.

Centrifugal pumps tend to be inexpensive, reliable, and easily repaired. They are the mainstay of most processes in the chemical process industries, including the pulp and paper industry.

Centrifugal pumps cannot perform well when large amounts of gas are in the system, unless some strategy is applied to remove the gas. Likewise, startup requires that the pump be primed with liquid to create suction to pull in fluid into the impeller. Self-priming pumps, which must be filled with fluid prior to the first operation, are available.

3.2. Positive displacement pumps

Positive displacement pumps mechanically open a volume to suction, increase the volume to take in flow, seal off the volume, then displace it to the discharge. Pressure is created as a system response to the motion of the discharged flow and any static head on the discharge.

Two types of positive displacement pumps have been used in pulp handling. The reciprocating plunger pump was used for many years for pulp up to 6%. These pumps have valves and were thus limited to low consistency application, where valve plugging was less likely. The other type, rotary positive displacement pumps are still widely used. These include lobe, gear, single screw, and two-screw types. Figure 6 shows examples of twin-screw and gear pumps that can be used for pumping medium consistency pulp. Standards and definitions for rotary positive displacement pumps have been provided by the Hydraulic Institute (26).

Positive displacement pumps can operate either with an open suction (no head of stock at the inlet) or with a suction head. Normally, pumps are run at a fixed speed or volumetric displacement rate slightly above the average rate of flow from the source to allow for normal fluctuations. The self-priming action of the pump displaces whatever pulp enters the suction. Usually a feeder is used (integral with the pump or a separate unit) to ensure that pulp reaches the suction entrance of the pump rotor.

The NPIP for a positive displacement pump can become important when a steam mixer is used before the pump, especially at temperatures over 80°C.

Steam bubbles in the stock may cavitate (collapsing violently) as the stock moves toward the high pressure end of the pump.

Inlet flow variations to a pump operating at fixed speed require the pump to handle a varying amount of air in open suction mode. This is readily done if the overcapacity remains around 10-25%. If run at much higher overcapacity to handle a larger range of flow rates, the pump is compressing and expelling large amounts of air and suffers from poor performance due to air slip (compressed air escaping through pump clearances, decreasing the discharge head).

Rotary positive displacement pumps tend to be self-priming. They are well suited to highly viscous flows. They tend to have high efficiency, resulting in lower energy costs. Air content and cavitation is often less a concern than in centrifugal pumps, but NPSHR ratings are usually more difficult to establish for rotary pumps, making cavitation problems sometimes difficult to predict. Open feed pumps, such as gear pumps and screw pumps for medium consistency pulp, may have no suction head requirements.

Positive displacement pumps can run easily with simple, fixed-speed drives and without vacuum systems or related control equipment.

Positive displacement pumps usually have large pumping cavities which permit them to handle a great deal of solids and foreign objects. However, objects larger than the cavity which resist breakup may jam the pump, causing stoppage. If stoppage occurs, the pump can often be reversed to allow removal of the offending object, with no serious damage to the pump.

Several possible disadvantages to positive displacement pumps must also be considered. Positive displacement pumps tend to be more expensive than centrifugal pumps. The cost may be higher by 50% or more for a given application. The higher purchase cost must be weighted against the lower costs achieved by higher efficiency, less peripheral equipment, and simpler operation.

If a positive displacement pump is damaged by foreign objects or other problems, repairs can be expensive (on the order of $30,000 for a typical pulp pump) due to the precise machining and small tolerances required. In some pumps, small changes in clearances due to wear may significantly decrease pump performance, so maintenance tends to be more frequent than for centrifugal pumps. Actual service needs vary widely depending on the type of pump, the application, and the preventative maintenance program.

4. Pumping of pulp

4.1. Low consistency pulp

Flow disturbances prior to the pump inlet such as elbows or bends will increase the likelihood of cavitation and increase the true NPSHR beyond the manufacturer's recommendation. Poor layout of the inlet piping to a pump is a common problem in the pulp and paper industries, contributing to the widespread occurrence of pump cavitation. Careful consideration of inlet pressure requirements is essential to designing a good pumping system. In designing a pump system, the highest possible pulp temperature that might be encountered in the line should be used in calculating the vapor pressure for NPSH estimations.

Horo and Niskanen (27) found that NPSHR values or centrifugal pumps were often not reliable for pulp suspensions, for the head required to avoid cavitation did not follow the expected trend as fluid temperature was changed. They found that a higher suction head is needed for pulp than for water, and the additional head required increases with consistency. Users of centrifugal pumps for stock should inquire how the NPSHR value was determined; if it was determined in water flow, additional head may be needed for pulp flow. A common problem with medium consistency pumps is that an increase in consistency will lead to a drop in pulp density that may lower the available suction head in a standpipe enough to cause cavitation.

A useful concept in failure analysis of pumps due to cavitation is suction specific speed, a parameter that describes inlet conditions for geometrically similar pumps (28).

Operating at excessively high speed is a well known cause of cavitation. Less known is the danger of operating at too low a speed or at too low a flow rate. In this case, the flow pattern in the pump changes; instead of regular streamlines leading from the inlet to the outlet, recirculation zones occur, with eddies of fluid spinning inside the pump. The flow separation that occurs may lead to damaging cavitation and loud noise in the pump. Cavitation damage can then occur even when the suction head available is well above the NPSHR. A review of several aspects of this problem is presented in (29). Furthermore, the thrust on the shaft and bearings will be much different than at normal speed, leading to an imbalance of forces that can cause premature failure of bearings.

To increase the NPSH of a system, several strategies can be considered (22). Solutions involving changes to the pump include:

- Using an oversized pump for applications with "small" head requirements. (High-head pumps operating at flow rates well below the intended range are subject to cavitation and excessive shaft stresses, as discussed above.)
- Using a double suction impeller design to reduce the NPSHR by roughly 25% at a given speed and flow rate.
- Use a low-speed pump. (However, these tend to be less efficient and more expensive than higher speed pumps.)
- Increasing the size of the impeller eye to reduce the velocities in the impeller inlet. (There is a danger of operating at too low a velocity if the

eye is oversized; in this case, internal recirculation can occur which will lower efficiency and shorten pump life.)

- Adding an inducer to the impeller.
- Using a multistage pump.
- Adding a small booster pump to increase the head in the suction line to the main pump.

NPSHR can also be increased by modifying the flow to the pump. Strategies include:

- Raising the head in the suction line, typically by raising the fluid level in the tank before the pump. This is often easiest solution.
- Cooling the liquid, often with a heat exchanger or injection of cold water.

Proper approach flow into the pump is critical for long life and good operation. This is one of the most abused aspects of hydraulic design in paper mills. A straight run into the suction side of the pump is preferred. Valves or other fittings should be avoided near the suction side of most pumps because they contribute to cavitation.

Users should insist that NPSH specifications for pumps have been properly obtained. Standards for testing have been defined by the Hydraulic Institute (24-26).

Air can enter the flow into a pump through leaks, packings, and through vortices that extend into tanks when liquid levels are low. Venting is sometimes needed to allow accumulated air to be removed. For centrifugal pumps, air content below three percent poses few problems, while 7% or greater may require a self-priming pump.

4.2. Medium consistency centrifugal pumps

Design principles

The advent of modern medium-consistency technology for the bleach plant came with the development of Kamyr's MC™ pump (now made by Ahlstrom), which combined pulp fluidization, degassing, and pumping in a single-shaft tower discharge unit. Gullichsen et al. (18,19) outline the path taken to achieve this. The manufacturer's current MC™ pumps are claimed to operate at consistencies up to 16%. Other centrifugal pumps for medium consistency pulp are now marketed by Goulds Pumps and Sunds Defibrator; these pumps will be described below.

The operation of medium consistency centrifugal pumps is typically based on high shear forces in the inlet throat to reach a fluid-like state in the pulp (see Figure 3), coupled with separation of gas entrained in the suspension. The typical medium consistency pump has five functional zones (see Figure 7):

A. A shear zone, where the fiber network is broken down and the suspension shows fluid-like behavior.

B. The gas separation zone where air or other gases are separated from the stock by centrifugal forces.

C. The pumping zone, where impeller vanes pump the stock towards the discharge.

D. A fiber return zone, where fibers entrained in the separated gas are returned to the pump discharge.

E. The degassing zone, where separated and purified gas is removed to the degassing unit.

Many of the differences between various medium consistency pumps on the market lie in the way gas is separated from the pulp and in the way the pulp is brought to the impeller. Four commercial examples are shown in Figure 8.

The Goulds medium consistency pump removes air through balance holes in the impeller shroud. A dynamic vane on the back of the impeller is part of the secondary separation strategy to separate fibers and air. The air may be connected to a vacuum line or to the atmosphere, depending on pumping conditions. As with the Ahlstrom design, an inducer is used to break up the fiber network entering the suction line. A consistency range up to 16% is claimed.

A past Sunds Defibrator pump (the CMB series) for medium consistency pulp features a centrifugal pump preceded by a screw feeder that is designed to oversupply the pump with pulp. As a result, there is overpressure in the pump housing inlet which forces a return flow of pulp through openings along the center of the feeder. This return flow removes some air from the pulp, making a separate air removal system unnecessary. The manufacturer claims a pulp consistency range of up to 12%.

A new pump design, developed jointly by Sunds Defibrator and ABS Pumps, does away with inducers and screw feeders before the impeller, placing the impeller directly against the face of the supply vessel. This is achieved with a modified impeller that offers a large open area for stable flow and provides for direct air removal. Like most centrifugal pumps for medium consistency pulp, a vacuum system is included for air removal, though it may not be necessary under stable operating conditions.

Operating guidelines

Fiber network properties vary. It is important to establish the impeller's minimum speed of rotation to bring stock of given consistency to the fluid-like state. The critical impeller speed may vary as stock properties change. The fiber suspension rapidly resumes its network character upon leaving the pump volute, returning to the plug flow regime.

The large volumes of gas present in typical medium consistency pulp can defeat centrifugal pumping unless proper degassing is performed. Without degassing, gas may accumulate in the rotational center until the pump housing is filled with gas. Since the pressure rise across the impeller is proportional to the density of the fluid, a gas-filled impeller generates negligible pumping power and pulp flow will cease. A suitable discharge gas flow must be maintained. This is achieved by creating a positive pressure differential between the pump inlet and the degassing line. No vacuum devices are needed if the suction side head is high enough. This is often not the case, so many pump installations include a vacuum pump. This can either be externally installed or built into the pump back end on the same shaft. Fibers will escape if the applied pressure difference is kept too high. Stable operation is reached when applied pressure differentials are in the range of 1-2 meters of water. The vacuum system should be interlocked with the pump drive.

Once the pump is properly tuned, up to 16% consistency can be pumped. However, if there are significant changes in the incoming pulp (especially a change in consistency), the degassing system of some pumps may be out of tune, resulting in inadequate gas removal or excessive fiber flow into the gas line. To avoid manual retuning, some mills simplify pump operation by disconnecting the degassing system and running at a lower consistency (say, 9-10%). Some new degassing systems offer improved stability of operation above 12% consistency.

Pulp flow out of the pump can be controlled by controlling the pump's speed of rotation with the limitation that the speed be above the minimum required for network disruption. Many installations use throttling for flow control. The choice of control valve is important; ball sector or v-sector ball valves are preferred to guarantee stable operation. Full bore ball valves or disc valves may give unstable operation. The control valve should be mounted as close as possible to the pump discharge and have the same free diameter as the discharge of the pump.

Centrifugal pumps for medium consistency pulp generally require few repairs, largely because they are designed to have large enough clearances to tolerate foreign materials that might be brought in with the pulp. They are generally built of stainless steel or titanium and can be mounted with the shaft horizontal or, for tower discharge, vertical.

The flow velocity in medium consistency pipelines is typically near 0.2 m/s. In some cases, this is not enough to avoid stick/slip motion or pulsations in the flow, and operation at higher velocities (say, 0.5 m/s) can result in improved performance.

Centrifugal medium-consistency pump efficiencies currently lie in the 35-45% range, well below that of positive displacement pumps. Manufacturers are actively working on improvements to lower operating costs. In some cases, energy lost due to low pump efficiency may be small compared to extra energy required for heating diluted stock in the bleach plant.

Standpipes for pulp flow to centrifugal pumps are an important aspect of medium consistency technology. New designs feature large columns (near 1 m diameter) with an inverse taper (the standpipe widens toward the ground) to prevent bridging and plugging. Dilution lines are present in the event the degassing system fails or other problems occur. It is important that the proper level of pulp be maintained in the standpipe. A common design head is 3 m. The level in the standpipe is usually controlled with a control valve downstream of the centrifugal medium consistency pump. Chemicals can be mixed into the pulp in the standpipe, and fully mixed as the pulp passes through the pump. In some cases, this mixing strategy can eliminate the need for a mixer downstream.

The rate of shear in the impeller zone of a typical medium consistency centrifugal pump exceeds, by orders of magnitude, what is required to break down the fiber network. This means that the pump itself can be used as a mixer with some limitations. For example, one manufacturer reports that roughly 3/4 of their medium consistency pumps in bleach plants are used for mixing. Reagents like NaOH and NaOCl which react slowly with pulp can be injected successfully in the pump inlet while chemicals like H_2O_2, $Na_2S_2O_4$, and H_2SO_4 have to be injected through a special nozzle located on the inlet throat. Chemicals with a high partial pressure like ClO_2 must be injected through a nozzle located on the pump volute in order to avoid gas escape through the degassing system. All other cases require separate mixers suitable for the medium consistency regime.

4.3. Positive displacement pumps

Positive displacement pumps for medium consistency have predominantly been of two types, rotary screw pumps and gear pumps. Most rotary screw or progressing cavity pumps for medium consistency pulp are twin-screw pumps, but single-rotor progressive cavity pumps are also found in some installations.

Twin-screw pumps

Twin-screw pumps carry fluid in the spaces between screw threads. The fluid moves axially as the threads rotate and mesh inside a closely fitting housing. The required pressure gain occurs as the volume between the threads progressively decreases due to either an axial increase in shaft diameter or an increase in thread thickness. The decreasing volume pressurizes the fluid. The major producer of twin-screw pumps for medium consistency pulp has been Warren Pumps. Figure 6a shows an example of such a pump. Twin-screw pumps were the most common means for pumping thick stock prior to the development of centrifugal medium consistency pumps in the 1980s and are still widely used.

Perhaps the main advantage of twin-screw pumps over centrifugal medium consistency pumps is the ability to handle higher ranges of pulp consistency. Current technology permits pumping stock up to 18% in consistency, and pumps that will handle up to 25% consistency are planned for the near future (in fact, three sites have installed twin-screw pumps to handle 20-25% consistency pulp, but further developments are required for this range to be easily handled). Typical week-to-week variations in pulp consistency do not have a dramatic effect on pump performance. A significant benefit for the bleach plant is the high flow uniformity possible with twin-screw pumps.

Other advantages of twin-screw pumps for medium consistency include lower energy costs and the ability to handle high gas content in the incoming stock. Unlike the centrifugal medium consistency pump, positive displacement pumps do not depend on high shear to create fluid-like behavior in the stock, a process that requires substantial power. This accounts for part of the energy savings with positive displacement pumps. Since degassing of the stock is not needed, a vacuum pump and the associated control equipment need not be purchased with the pump. However, for some bleaching processes (especially hydrosulfite bleaching), the presence of air would be harmful, so degassing may be needed anyway. If the pulp is pumped with some air content, further energy savings may be achieved because of the friction-lowering effect of air in medium consistency pulp (30). Apparently the air acts as a lubricant between the pulp and the pipe wall, lowering friction. At 14% consistency, for example, the energy savings due to decreased pipe friction may be on the order of 50% compared to pumping degassed pulp. One mechanism that may be important in achieving this friction reduction is the relatively long dwell time the pulp suspension has in the twin-screw pump. The shear in the pump folds in and disperses the air in the pulp. Much of the air is removed from the pump by an air bleed valve, but a portion is still present in the discharged pulp. If the air were not well dispersed, slug flow and large pulsations could occur.

Capital costs for twin-screw pumps are 40-100% higher than medium consistency centrifugal pumps. Although the pulp is usually free of harmful foreign objects in the bleach plant, there may be high maintenance costs if damage occurs. (Foreign objects that might cause problems are usually due to poor maintenance; for example, damaged repulper blades that are not replaced can eventually fail and enter a pump, or damaged screen straps from a washer drum may break off and fall into the pulp.)

Positive displacement pumps tend to do much less mixing of the pulp than centrifugal pumps, which is not necessarily a disadvantage unless the chemical mixing systems of the bleach line are marginal.

The design of the feed system for a positive displacement pump is important. If proper guidelines are not followed, bridging of the pulp in a feed chute may occur, especially above 14% consistency. The feed line should have straight, vertical walls, no obstructions, and the diameter dimensioned so that the friction loss per foot in the chute is less than static head per foot of pulp.

Single-screw pumps

Similar in principle to twin-screw pumps, single-rotor or eccentric-screw pumps are progressive cavity pumps in which the moving cavities are formed between a rotor, with a single external helical thread, and the stator, with a double internal helical thread. The rotor is made from hard metal (e.g., stainless steel, titanium, or other alloys), while the stator is an elastomeric material bound to a metal housing. Though single-rotor pumps are not commonly used for medium consistency pulp, such use is increasing in North America. Robbins and Meyers, Inc., is a major manufacturer of single-rotor pumps (Moyno® pumps) for medium consistency pulp, with a claimed range of 6 to 16% consistency.

As with twin-screw pumps, low pulp shear and low energy use are claimed advantages for single-rotor pumps. Low cost of installation is another claimed advantage over centrifugal pumps. Single-rotor medium consistency pumps feature open-throat positive auger feed that does not require air removal from the stock. Heads up to 1 MPa (150 psig) can be generated.

The elastomeric stators are available in various formulations for specific pulping and bleaching conditions. In bleaching operations, bleach chemicals can sometimes be added at the auger feed or in a section between the feed and the stator.

Gear pumps

Gear pumps depend on the relative movement between rotating elements and the pump housing. Fluid is trapped in spaces between gear teeth and moved from the inlet to the outlet. Pressurization is achieved by a progressively decreasing pumping volume as the fluid approaches the outlet. The primary manufacturer of gear pumps for medium consistency pulp is IMPCO Division of Ingersoll-Rand, which produces a dual-gear pump (see Figure 6b) and a single-gear pump which intermeshes with a screw to drive the pulp. The latter system (termed Clove-Rotor™) can handle consistencies up to 35%. At high consistency, naturally, the pulp cannot be pumped long distances due to the high pressure drop, the danger of plugging and the risk of intense vibrations, but the pump is used to feed some high consistency processes and storage tanks. Most gear pump installations in bleach plants are for medium consistency operation (some users give a limit of roughly 14% for "typical" operations such as feeding the top of a tower from ground level). Oxygen delignification and bleaching stages are common candidates for this pump.

Besides a broad consistency range, these pumps offer other advantages. No discharge control valve or other control equipment is required, no priming is necessary, degassing systems are not needed, efficiency is high, and friction losses in the pulp are claimed to be 5-10% lower than when pumped by centrifugal pumps because of a friction-lowering effect from the air in the pulp (the difference in pulp-gas mixing may account for the different degrees of friction reduction obtained by the gear and twin-screw pumps, with the latter being capable of greater friction reduction in many cases). There also tend to be fewer problems with pulp feed to the pump, perhaps, because of the mechanical vibration of the feed system induced by the pump itself.

While the gear pump for medium consistency pulp has been a long-used device, it is inherently subject to flow pulsations as the gears sweep through the casing. These pulsations induce a stick/slip motion in the pipeline, where the cycle of acceleration/deceleration increases the normal friction losses. Air content can be a problem, as the air is not well dispersed in the pulp during its brief passage through the pump. Slug flow can occur, leading to large pulsations in the line. In medium consistency flow, the pulsations can be severe enough to cause hammering that can rupture steel piping. Some gear pump users report the need to dilute the stock below 10% consistency to avoid pulsations. By reducing air content, avoiding steam mixing just before the pump, and controlling pulp properties, steady operation with medium consistency pulp above 10% is possible.

4.4. Design of medium consistency systems

Medium consistency pumps can be used in many applications (see Figure 9). The most common applications are pumping from a dropleg and tower discharge pumping. For tower discharge, a scraper is often needed in the tower bottom (as shown in Figure 9) but this is not mandatory. No tower scrapers are required if one can accept that some pulp is left in the tower on emptying.

Medium consistency pumps can be used to feed several stock lines, one by one or several lines simultaneously as shown in Figure 9. The latter case requires that the flow splitter be equipped with a rotating device to break down the fiber network prior to flow splitting. Medium consistency pumping can be used for long distance transportation (several hundred meters) by installing pumps in series. Only the first pump in the chain needs degassing, the rest can do without.

Delivery of medium consistency pulp into a pump deserves special attention. Centrifugal pumps require a certain head of pulp over the pump inlet to establish flow, while open suction pumps must have a feeder to physically move the material into the pumping rotor. In designing the feed system to a pump, the relation between stock density and frictional head losses in the chute must be considered. As consistency increases, the density of the stock decreases and the network strength and wall friction increase, making bridging and other feed problems more likely. Figure 10a shows the suction head available per foot in a vertical column of pulp, while Figure 10b shows the frictional head loss for 18% consistency pulp in a rectangular feed chute (50 cm x 85 cm) as a function of flow rate (31). Above 500 tpd, the frictional losses in the chute would exceed the head due to gravity. In this case, bridging may occur in the chute or the flow rate may become erratic. A feed screw or agitator in the feeder may then be necessary.

The velocity of the stock plays an important role in the stability of a hydraulic system. For typical pipelines, velocities of 0.15-0.5 m/s are generally preferred. At velocities below 0.15 m/s, there may be partial separation of the phases (water, air, and fibers), which, in some cases, could lead to pipeline pulsations, plugging of valves, or nonuniform flow. In practice, pipelines with medium consistency centrifugal pumps tend to run in the range of 0.15-0.3 m/s, while lines fed by positive displacement pumps may run up to 0.5 m/s.

Flow stability is essential for mixing and refining. Better stability is achieved with higher velocity. For stable flow at medium consistency, the flow velocity from the pump should be at least 2 m/s. The velocity should be even further increased just before the flow enters a refiner. For mixers and refiners, the distance from the pump should be kept under 10 m, if possible. If the line must be longer, the velocity should be maintained at 0.3 to 0.6 m/s for most of the distance, then increased in an abrupt step (via a reduction in pipe diameter) to a velocity of at least 2 m/s to stabilize the flow (31).

While pipelines for medium consistency stock should be kept as short as possible to avoid pulsations and to conserve energy, long transfer lines can be run with little pulsation if the flow velocity is maintained in the 0.15-0.6 m/s range. If the flow velocity becomes low (<0.15 m/s) and if there are perturbations such as a series of valves and elbows downstream of a long straight run, large pulsations may take place. These pulsations are the results of the combination of a compressible air-laden volume which alternately compresses and expands as it approaches and passes zones of increased flow resistance (obstacles). Pumps which remove much of the air, such as centrifugal pumps or twin-screw pumps, decrease the likelihood of pulsations.

5. General considerations for design of pumping and piping systems

An excellent discussion of design considerations for slurry pumps in general is offered by Wilson et al. (32). Guidelines for centrifugal stock pumps are given in TAPPI Technical Information Sheet 0420-10 (33).

5.1. Power requirements and pipe size

Many pump systems have been overdesigned due to uncertainties in pulp friction. Improved data for practical fiber suspension flows are needed. There is a great need for laboratory tests that could be used to accurately predict the flow properties of a pulp. Currently, no set of tests is entirely adequate.

One of the major problems is that the data used for design are based on measurements in ideal piping systems with long, straight runs, whereas, the piping systems in typical mills are a maze of elbows, valves, and joints. For example, in designing the pumping system for a bleach plant, one paper company recently reported that various sets of correlations for pressure drop were as much as 200% in error, with most of the error due to the pressure drop in elbows. There is a serious need to better understand pulp flow in elbows and other nonideal flow geometries.

Pressure drop predictions for typical medium consistency operation are generally reasonably accurate. For example, correlations for medium consistency transport using twin-screw pumps have been verified over a 35-year period, and typically predict pressure drop within 10% if a small to moderate amount of air is present, and if the velocity is at least 0.15 m/s.

It is important to know the full range of pulp consistency that a pump will encounter during normal operation, as well as the range of flow rates and the range of discharge head. The pump should be able to handle the most extreme requirements to be imposed on it without being overburdened. Sudden decreases in pulp consistency also must be considered, as a lower consistency may let the pump surge to too high a flow rate that might overstress the pump (34).

5.2. Sizing pumps

As energy and capital equipment costs have become more important considerations in selecting a pump, purchasers now increasingly seek the smallest, most energy-efficient pump that can meet specifications. At the same time, existing mills often seek to push their equipment beyond the original specifications, which sometimes results in pumps being operated beyond the best efficiency point in a region where cavitation damage, erosion, and excessive shaft stresses may occur. The result is shortened pump life. It is wise to anticipate the possibility of future flow increases in a system and to carefully consider the economic trade-offs between pump size, operating costs, and pump life in off-design flows.

Optimum performance of a pump occurs at only one point on the three-dimensional surface plot of kinetic head as a function of speed and flow rate. Users should not overemphasize pump efficiency at the expense of pump lifetime and overall performance across the expected range of pumping conditions.

5.3. Materials for pumps and pipes

In the bleach plant, stainless steel alloys are the dominant materials of construction for modern pumps. Cast iron casings are still common. Modern impellers are no longer bronze or iron, but are overwhelmingly stainless steel. Rubber or polymer linings, which may break off with wear, are less used. When bleaching chemicals are injected directly into the pump, special materials are often needed. For chlorine dioxide injection, titanium is often specified. If chlorine is injected into a pump (not common), or if high residual chlorine will pass through a pump, Hastelloy or other chlorine-resistance alloys are needed; titanium is not recommended. In medium consistency pumps for ozone bleaching, 317 stainless steel is preferred. For oxygen treatments, stainless steel is usually adequate.

While fiberglass has proven useful in some low consistency pipelines, pulsations in medium consistency flow may lead to rupture, especially at elbows. High strength piping (stainless steel or titanium) is usually used for elbows.

5.4. Pressure measurement

Pressure measurement is recommended in both the suction line and the discharge line. Previously, Boudon gauges were used, but electric pressure transducers are now recommended. Ring-type tapping points should be located no closer than one pipe diameter past the pump discharge. Lines connecting tapping points to a transducer should have valving to permit backflushing with water.

5.5. Partial flow

In the design of hydraulic systems, pump performance at the best efficiency point (B.E.P.) is often the main factor considered. However, temporary swings and long-term modifications often result in off-design flow conditions which shorten pump life. It is important to plan for reduced flow conditions, especially when oversized pumps are used. Pump damage at low flow is a common problem and is much different than the problems that occur at high flow or with low NPSH.

Bypass loops that recirculate part of the flow are a common means of operating at low flow without damage to the pump. The temperature rise in the pump is the key factor to consider in determining the amount of recirculation (Garay, p. 107). Garay discusses several options for recirculating flow control (p. 128 ff.).

Low NPSHR pumps (especially those with large impeller eyes) may experience low-frequency pulsations (8Hz or less) under low-flow conditions with internal recirculation in the impeller eye. Impeller vane inlet angles at low flow do not correspond well to the flow, leading to flow separation on the back of impeller vanes, which in turn can cause cavitation. This problem is not easily detected by head loss, as is normal cavitation from inadequate NPSH.

5.6. Elbows, valves, flanges, supports

Control valves are commonly required on the discharge side of centrifugal medium consistency pumps to regulate the flow rate. Valves or other fittings should be avoided near the suction side of most pumps because they contribute to cavitation.

Medium consistency process and transfer lines are normally sized for low flow velocity and are thus large in diameter. These lines, when full, have great weight, yet usually have small structural stiffness (pipes are typically Schedule 10 to Schedule 40). This requires special care with pipe supports. A further problem is the large thermal expansion that can occur when the pipes are heated from room temperature to process temperature, which leads to large forces and moments on pump flanges. Therefore, discharge lines should be rigidly supported near the pump. Poor piping support or simple fulcrum-type support near the pump is the primary factor requiring pump maintenance for medium consistency applications.

Pulsations in medium consistency flows is a common problem, especially at or above 14% consistency. Pipelines should be firmly anchored, rather than supported by hangers, and bends or elbows should be supported with thrust blocks to prevent deflection. In medium consistency pipelines, more stable operation has been experienced with 90° elbows as opposed to 45° elbows (35).

5.7. Pump drive trains

The power demand of a pump is given by

$$\text{Power} = \frac{Q\Delta P}{\eta}$$

where Q is the volumetric flow rate of the pulp suspension (m^3/s), ΔP is the pressure gain across the pump, and η is the fractional pump efficiency. ΔP can be expressed in terms of the hydraulic head in height of suspension:

$$\Delta P = \rho_s g H$$

where ρ_s is the suspension density, g is gravitational acceleration, and H is the hydraulic head in units of length.

For many pumps, the pressure gain delivered will decrease as the flow rate is increased, often resulting in a maximum pump power at some flow rate.

Direct drives for slurry pumps are not common. Generally drives for pulp pumps operate at a fixed high speed (e.g., 1750 rpm) with a speed reducer and coupling connected to the pump. Gears and V-belts can be used to adjust shaft speed.

Variable speed drives allow great flexibility in mill operation, but are less efficient and more expensive than fixed-speed motors. However, they can provide large cost savings for mills that frequently vary tonnage rates or consistency. Variable frequency drives should be considered for mills that use many storage tanks, for the tanks allow substantial flexibility in operation which usually means that flow rates and consistencies through a given pump are likely to vary frequently. Variable frequency drives are also of great value during start up, as the ability to gradually increase flows and pressures decreases the likelihood of water hammer and increases the life of the pump by decreasing start up stresses.

Shaft couplings should be chosen to permit pump operation even when shaft misalignment occurs, and to allow impeller clearance to be adjusted as wear occurs.

Base plates are important in maintaining pump alignment. The plate must be able to resist high torque and vibrations. When high pump loads are required, a stress analysis of the pumps and pipes may be needed. A well grouted baseplate and properly supported pipe are essential to good operation. If an expansion joint is used to decouple piping forces and moments on the pump discharge, it must have tie rods set to prevent piping pressure load from overloading the pump flange.

5.8. Seals

While most stock pumps in Europe use mechanical seals, packing dominates in North America. One representative of a major pump supplier noted that 95% of the low consistency pumps they sell use packings rather than seals. However, the trend is clearly away from packings and towards mechanical seals. This trend is driven primarily by environmental concerns. Packings increase water use and result in more effluent, though they are simple and inexpensive. A conversion to mechanical seals may be necessary for many applications, not only to reduce water consumption but also to prevent pollution from leaks. Expeller type seals are used in some pulp applications where dilution is undesirable; however, these are associated with efficiency losses typically on the order of 3% (36).

For medium consistency pumps, double mechanical seals are the standard. These are required for the vacuum air-removal system to function properly. Double mechanical seals are commonly used in applications where a pump may run dry. They prevent leakage from the pump and prevent dilution of the stock. Chlorine dioxide bleaching stages increasingly use double mechanical seals to stop leakage contributing to effluent.

Split seal technology has become relatively popular in the pulp and paper industry because the seals are easy to install. Cartridge seals are also finding increased acceptance.

Useful guidelines for meeting environmental regulations with mechanical seals are given in (37). Specific guidelines for the pulp and paper industry are published by TAPPI (38).

5.9. Potential of sealless pumps

A variety of sealless pumps, such as magnetic pumps, offer complete protection against leakage and dilution. High expense and the inability to run dry are disadvantages of these systems, but they are finding applications for chemical delivery systems.

5.10. Filtrate air

Filtrate lines from washers in bleach plants should have large retention tanks to allow good removal of air. Entrained air in the filtrate can lead to severe damage in subsequent stock pumps. Air in the stock also reduces filtration efficiency and lowers washing capacity. New pump and filter systems have been developed in recent years to remove air from filtrate lines.

5.11. Maintenance

Pumps for the pulp and paper industry have some of the highest mean time between failures of all available industrial pumps, permitting continuous operation for many months. Failures still occur, especially when the pump is operated poorly. It is wise to keep a spare rotating assembly for every pump to ensure that pump failures result in minimized down time.

Pumps can be damaged in many ways: by flow too far below or above the best efficiency point, by too low suction head, by improper startup, by sudden changes in consistency, and so on. Regular inspection and maintenance is vital. Visual inspection of pump parts is important: the observations should be recorded to permit analysis of changes and trends. Impeller inlets, blade surfaces, and corners between vanes and shroud should be checked, as should the pump shaft. Photographs are a useful tool. A mirror may help provide access to the back of vanes. Inspections may be spaced with intervals of a few months to a year, but inspections should be held after the first startup and after significant changes in operating conditions.

More sophisticated inspection tools may be applied for critical applications, if desired. These tools include hydrophones for signal analysis and accelerometers for vibration signature analysis.

Operating conditions should be recorded regularly: these include consistency, temperature, pH, pulp type, chemical concentrations, speed, flow rate, discharge head, and suction head. For critical pumps, this data should be evaluated jointly with the manufacturer.

Regular inspection and troubleshooting of mechanical seals is especially important. Only 5% of these precision devices achieve their expected lifetime; most fail early because of improper operation and poor maintenance (39).

In all cases, a proactive policy of regular maintenance and inspection to prevent pump damage is recommended instead of troubleshooting once problems set in.

5.12. Control and stability issues

For controlling flow rate, past strategy has typically called for control valves to throttle the flow being pumped by constant-speed motors. A modern trend, especially outside North America, is to use variable-speed drives instead of control valves. This may be economic when the pump power exceeds 25 kW.

Positive displacement pumps do not require regulation and must not be regulated with a valve.

Principles of pump control and stability are presented in the *Pump Handbook* of Karassik et al. (40).

5.13. Startup

For pumps with heated fluids, it is wise to warm up a pump before startup to prevent misalignments or high stresses due to strong thermal gradients. Garay (p. 124) advises that all parts of a pump should be held within 25°C of each other. Pumping hot fluids (fluids hotter than the pump by 35°C or more) with a cold or partially warmed-up pump may damage the pump severely.

Water hammer can occur during pump startup, and needs to be carefully considered. When a surge of fluid slams into an empty elbow or valve, a shock wave can be generated that can damage the pipeline, even rupturing components. When a pump is turned off, pulp may drain, resulting in evacuated regions that can contribute to hammering. A solution is to gradually increase the flow on startup, beginning with closed discharge valves that are slowly opened manually, or by installing automatic ramping valves on discharge piping. (Positive displacement pumps must not have discharge valves.) Variable-speed drives, if available, can be used to ramp the startup velocity.

5.14. Flow metering

Magnetic-flux meters, or simply magmeters, are generally preferred for measurement of flow rates in pulp suspensions and other slurries. These meters do not interfere with the flow, offer high accuracy (0.5% of full scale is commonly claimed), and can remain accurate over a wide range of consistencies (low and medium consistency flows). The reading from magmeters is proportional to the velocity of the conductive fluid (water) passing through a magnetic field; it does not directly measure the mass or liquid volumetric flow rate. If there is a significant amount of gas in the flow, the flow rate obtained from the meter will be inflated because the velocity of the pulp suspension at a given mass flow must increase as the volume fraction of liquid in the pipe is decreased (void volume is increased).

Magnetic flow meters should be of a low frequency impulse type which is less sensitive to entrained gas in the suspension. Recommended magnetic flowmeter location is on a straight pipe as close as possible to the pump discharge and before the control valve, where suspension velocity is still high. Magmeters are susceptible to stray electric fields, and must be properly grounded.

Ultrasonic flowmeters are often used for low consistency flows. The most common technologies employed are Doppler meters and transit-time meters. Doppler meters measure the frequency shift of an ultrasonic signal imparted by the moving fluid to determine fluid velocity. Transit-time meters determine fluid velocity by the difference in the time of flight for ultrasonic signals traveling upstream and downstream. Doppler meters require particulates or bubbles in a flow to scatter the signal and impart a Doppler shift to an ultrasonic signal, and can work well in dilute pulp suspensions (0.1% to 4% may be general good range, with measurements at higher consistencies possible depending on the instrument and the pipe). With proper calibration for a particular pulp, Doppler meters may have accuracy near 1%. Transit-time meters are capable of high accuracy with little calibration, but are unlikely to succeed at consistencies above about 2% because of signal attenuation (41). If many gas bubbles are present, the transit-time meter is likely to fail at even lower consistency.

Both types of ultrasonic meters are available as fixed installations and portable clamp-on units. Clamp-on units may have less accuracy because they can be influenced by defects and variations in pipe properties and by variation in the installation, but are useful in auditing flow systems.

6. Acknowledgment

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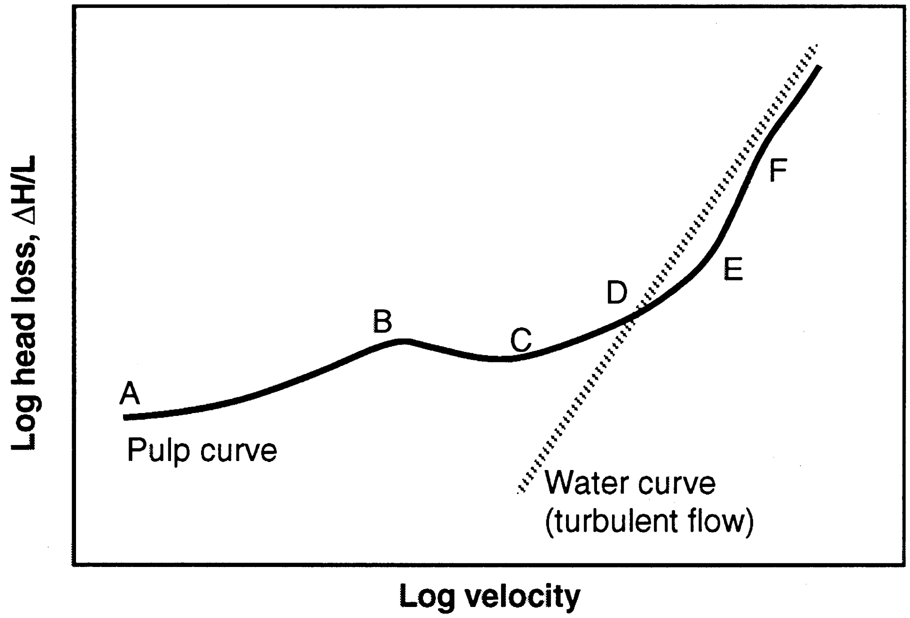


Figure 1. Comparison of head loss curves for water and a pulp suspension.

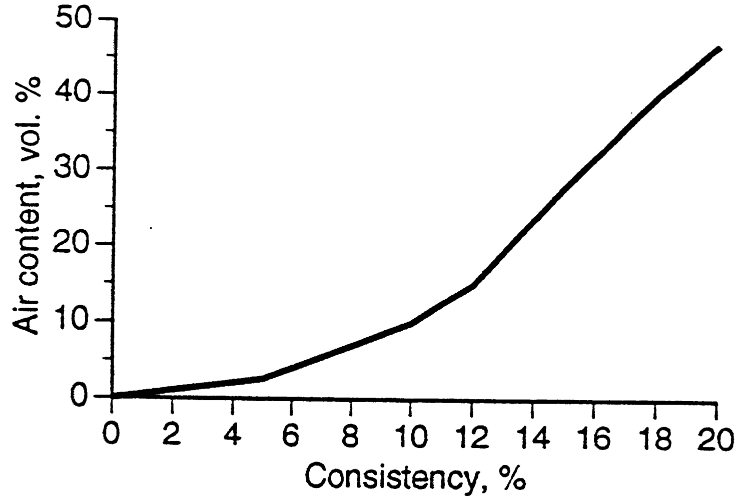


Figure 2. Typical results for air content in pulp.

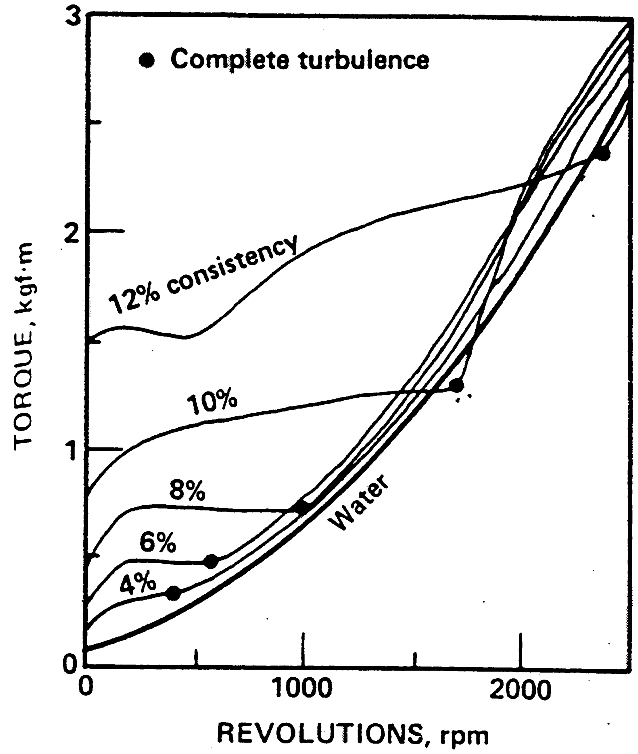


Figure 3. Rotational shear data in medium consistency pulp (18).

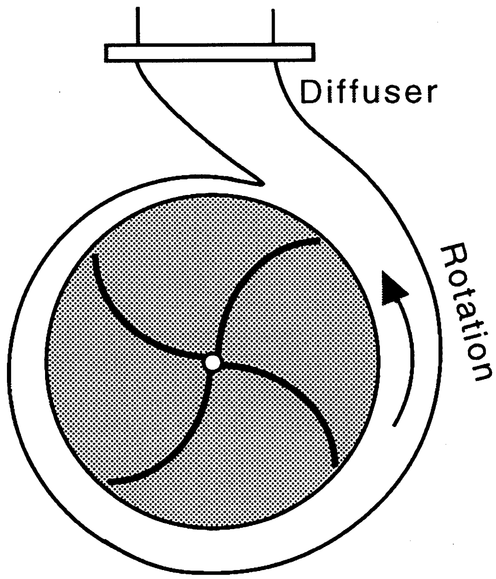


Figure 4. Cross section of a centrifugal pump showing impeller in the casing.

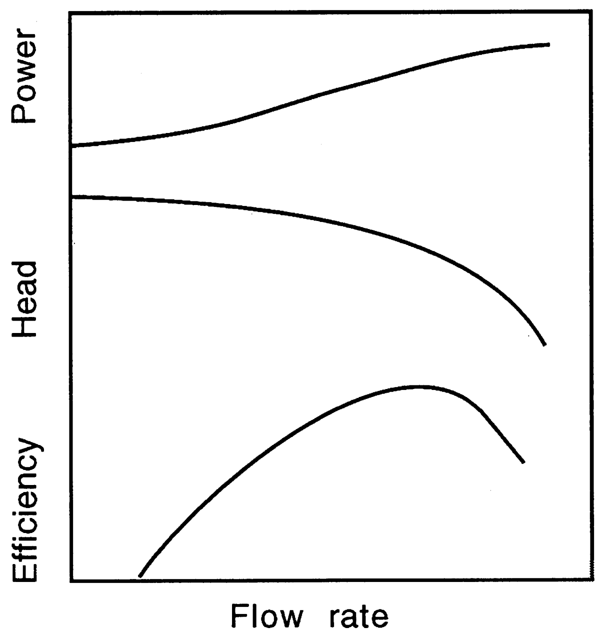
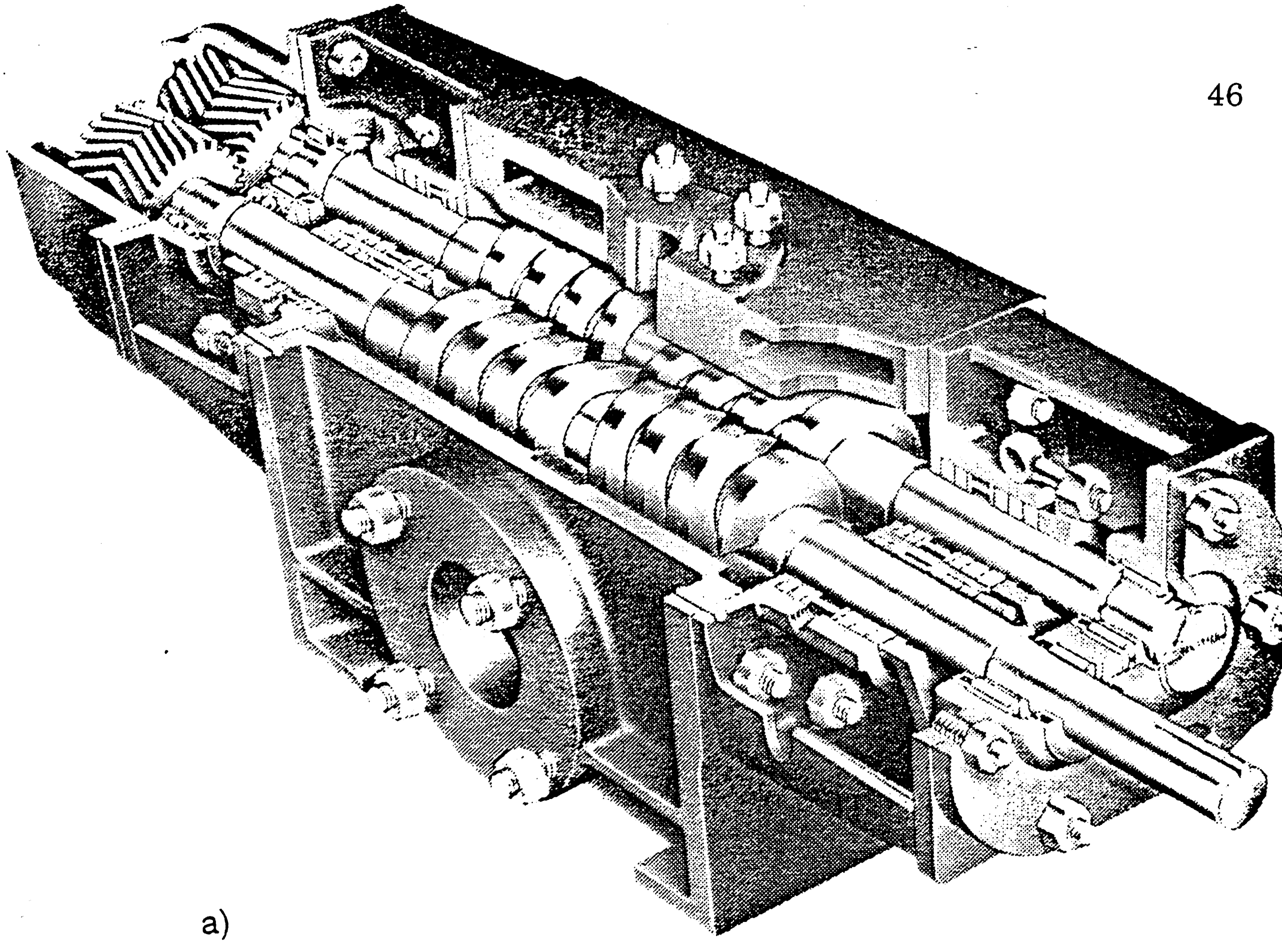


Figure 5. Typical centrifugal pump performance curves.



a)

b)

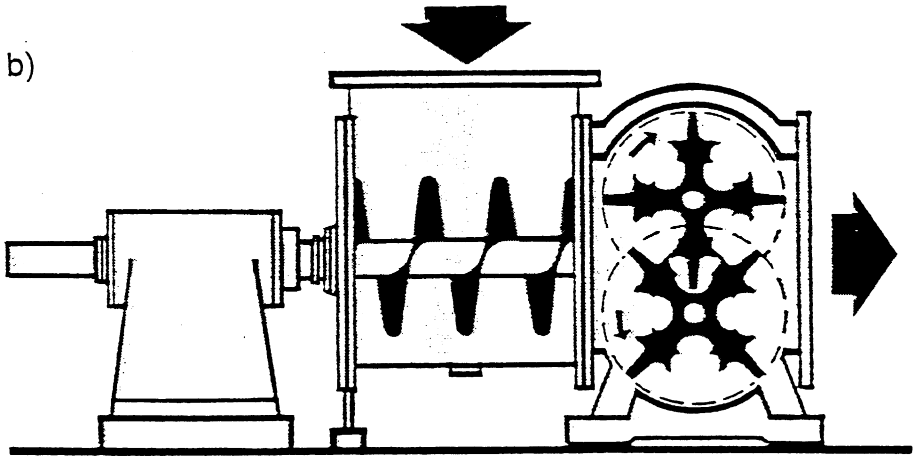


Figure 6. Positive displacement pumps for pulp pumping: a) a twin-screw pump (Warren pumps); b) a gear pump (IMPCO Division of Ingersoll-Rand).

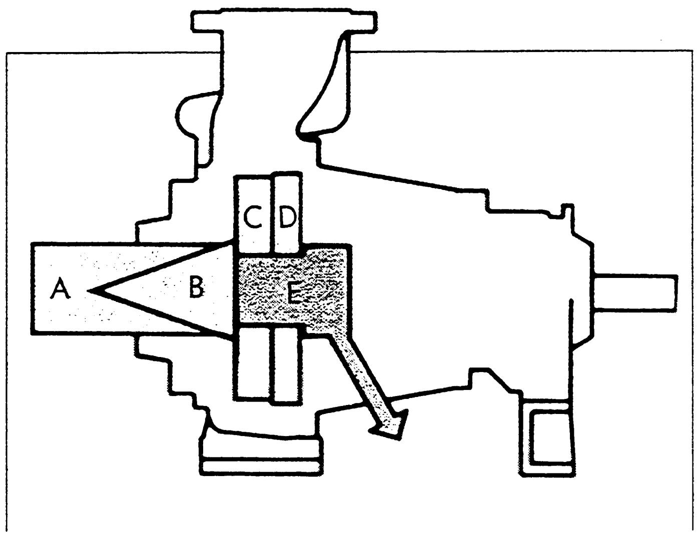


Figure 7. Zones of the impeller for a typical centrifugal pump for medium consistency pulp.

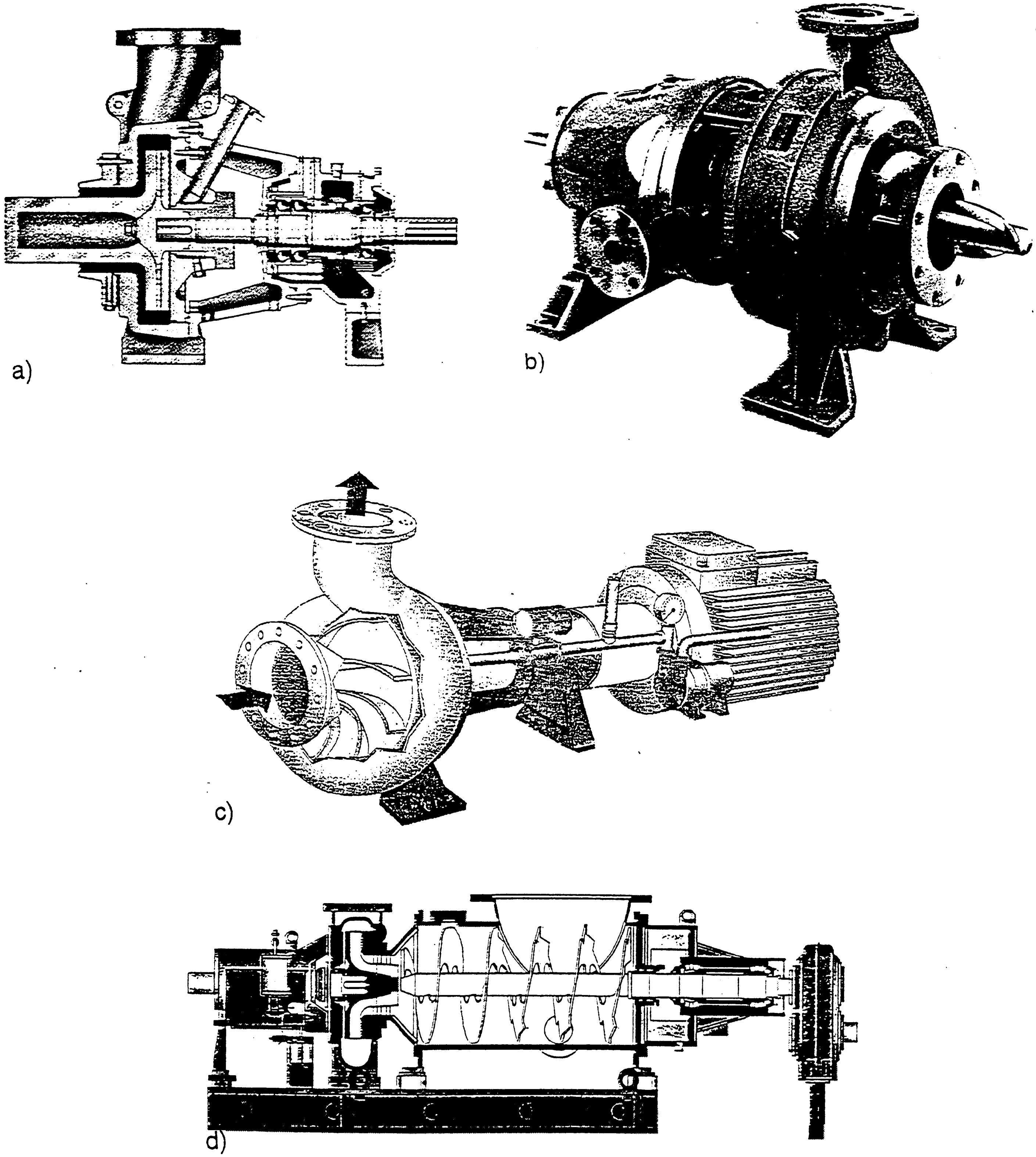


Figure 8. Four commercial medium consistency centrifugal pumps: a) Ahlstrom MC™ pump, b) Goulds Model 3500, c) current Sunds Defibrator pump, d) past Sunds Defibrator CMB series.

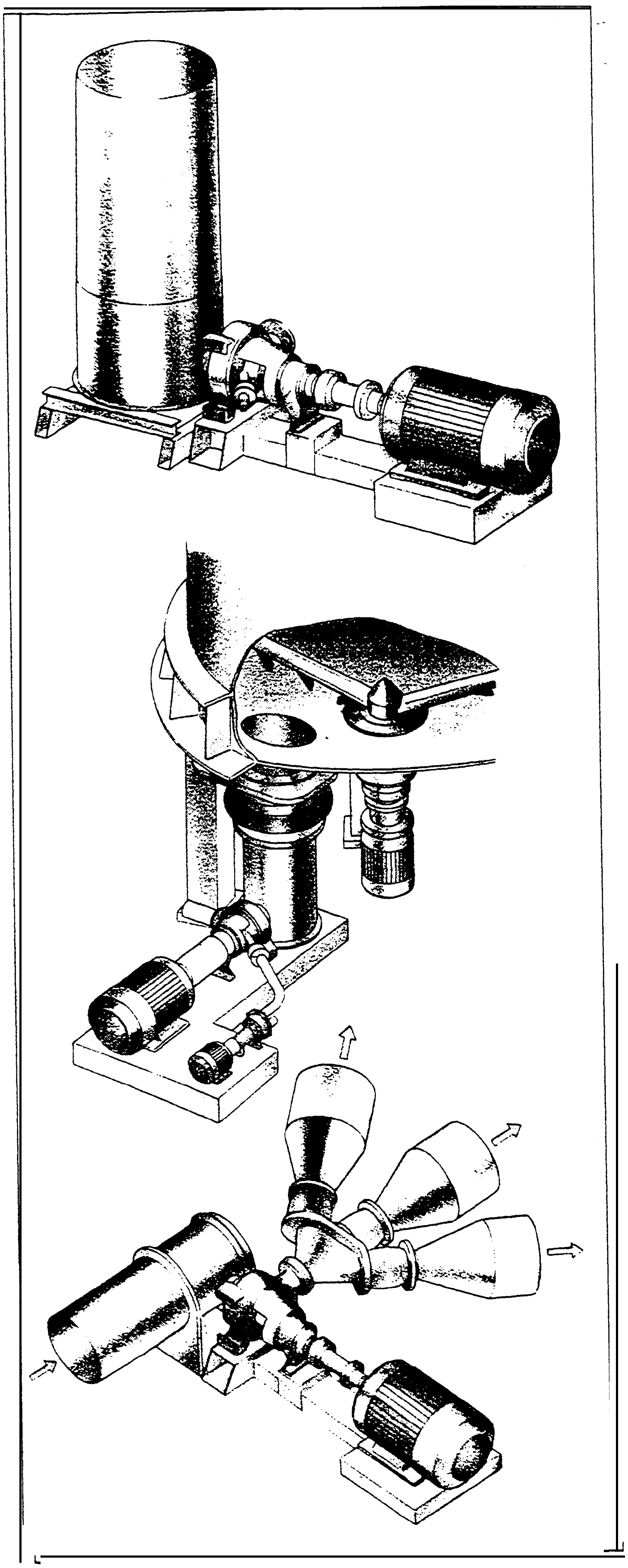


Figure 9. Use of medium consistency pumps for high density storage tower discharge (Ahlstrom).

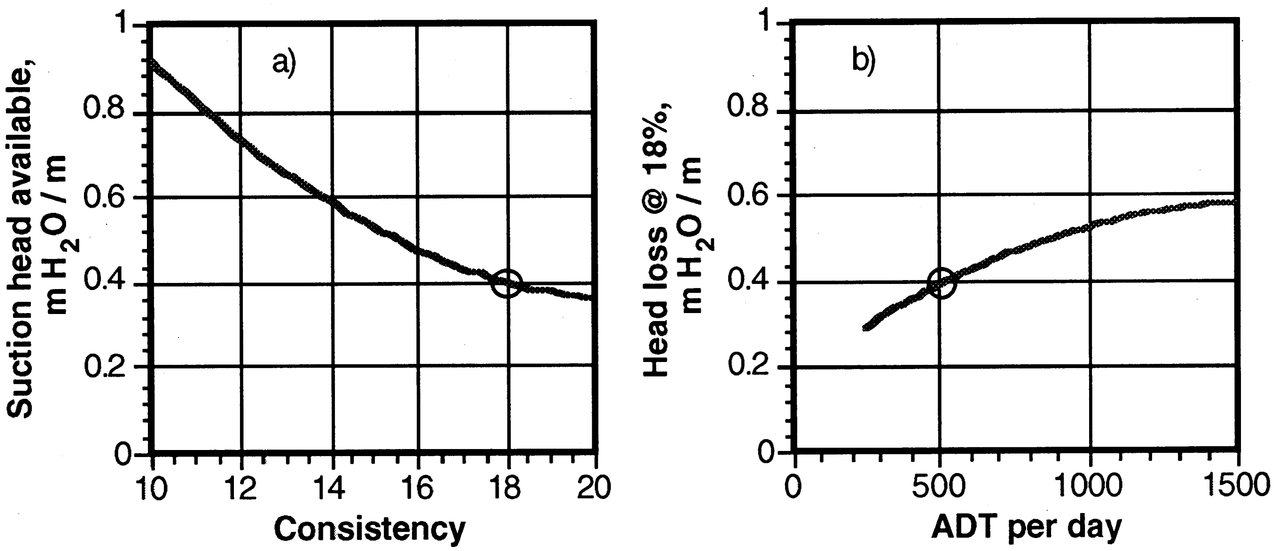


Figure 10. Relationships between suction head and head loss in the feed chute for medium consistency flow. a) Available suction head per meter of stock as a function of consistency. b) Frictional losses in the chute for 18% stock as a function of flow rate (31).